STAR FORMATION

A far-ultraviolet–driven photoevaporation flow observed in a protoplanetary disk

Olivier Berné[1]*, Emilie Habart[2], Els Peeters[3,4,5], Ilane Schroetter[1], Amélie Canin[1], Ameek Sidhu[3,4], Ryan Chown[3,4], Emeric Bron[6], Thomas J. Haworth[7], Pamela Klaassen[8], Boris Trahin[2], Dries Van De Putte[9], Felipe Alarcón[10], Marion Zannese[2], Alain Abergel[2], Edwin A. Bergin[10], Jeronimo Bernard-Salas[11,12], Christiaan Boersma[13], Jan Cami[3,4,5], Sara Cuadrado[14], Emmanuel Dartois[15], Daniel Dicken[2], Meriem Elyajouri[2], Asunción Fuente[16], Javier R. Goicoechea[14], Karl D. Gordon[9,17], Lina Issa[1], Christine Joblin[1], Olga Kannavou[2], Baria Khan[3], Ozan Lacinbala[2], David Languignon[6], Romane Le Gal[1,18,19], Alexandros Maragkoudakis[13], Raphael Meshaka[2], Yoko Okada[20], Takashi Onaka[21,22], Sofia Pasquini[3], Marc W. Pound[23], Massimo Robberto[9,17], Markus Röllig[20], Bethany Schefter[3], Thiébaut Schirmer[2,24], Thomas Simmer[2], Benoit Tabone[2], Alexander G. G. M. Tielens[23,25], Sílvia Vicente[26], Mark G. Wolfire[23], PDRs4All Team†

Most low-mass stars form in stellar clusters that also contain massive stars, which are sources of far-ultraviolet (FUV) radiation. Theoretical models predict that this FUV radiation produces photodissociation regions (PDRs) on the surfaces of protoplanetary disks around low-mass stars, which affects planet formation within the disks. We report James Webb Space Telescope and Atacama Large Millimeter Array observations of a FUV-irradiated protoplanetary disk in the Orion Nebula. Emission lines are detected from the PDR; modeling their kinematics and excitation allowed us to constrain the physical conditions within the gas. We quantified the mass-loss rate induced by the FUV irradiation and found that it is sufficient to remove gas from the disk in less than a million years. This is rapid enough to affect giant planet formation in the disk.

Young low-mass stars are surrounded by protoplanetary disks of gas and dust, which have lifetimes of a few million years (*1*–*3*) and are the sites of planet formation (*4*). Planet formation is limited by processes that remove mass from the disk, such as photoevaporation (*5*). This occurs when the upper layers of protoplanetary disks are heated by x-ray or ultraviolet photons. Radiative heating increases the gas temperature, which brings the local sound speed above the escape velocity of the disk, causing the gas to escape from the system. Those photons could be from the central star (*6*) or from nearby massive stars (*7*). Because most low-mass stars form in clusters that also contain massive stars, most protoplanetary disks are exposed to external radiation, and so they are expected to experience photoevaporation driven by ultraviolet photons during their lifetime (*7*–*11*). Theoretical models predict that far-ultraviolet (FUV) photons, those with energies below the Lyman limit (energy $E < 13.6$ eV), dominate the photoevaporation process. The effect affects the disk mass, radius, and lifetime (*7*, *10*, *12*–*18*); its chemical evolution (*19*–*21*); and the growth and migration of any planets forming within the disk (*22*). However, these processes have not been directly observed.

Most observational constraints on the mass-loss rates associated with photoionization have been obtained for objects in the Orion Nebula known as proplyds, in which the ionization of FUV-driven photoevaporation flows from disks produces comet-shaped ionization fronts (*23*, *24*). Modeling of the observed ionization fronts of proplyds has indicated mass-loss rates $\dot{M} \approx 10^{-8}$ to 10^{-6} solar masses per year ($M_\odot$ year^{-1}) (*25*–*27*). However, those observations did not determine the physical conditions (radiation field, gas temperature, and density) at the locations where the photoevaporation flows are launched.

In the regions where FUV photons penet the disk, a photodissociation region (PDR) (*28*) forms at the disk surface. Most observational tracers of PDR physics (spectral lines of H_2, O, and C^+) are in the near- and far-infrared wavelength ranges. The spatial scale of PDRs in externally illuminated disks is a few hundred astronomical units (au), which corresponds to angular sizes <1 arc sec (″) for the closest star-forming clusters (*12*, *29*, *30*).

Images of a photoevaporation flow

Figure 1 shows optical and near-infrared images of the Orion Bar, a ridge in the Orion Nebula (*31*) situated about 0.25 pc southeast of the Trapezium Cluster of massive stars. The western edge of the bar constitutes the ionization front (Fig. 1B), which separates regions where the gas is fully ionized and at temperature $T \sim 10^4$ K from the neutral atomic region at $T \sim 500$ to 1000 K. We investigated the source [BOM2000] d203-506 (hereafter d203-506) (*32*, *33*), a protoplanetary disk seen in absorption against the bright background, which is located at the following coordinates: right ascension $5^{h}35^{m}20^{s}.357$ and declination $-5°25'05''.81$ (J2000 equinox). Previous observations of d203-506 found no sign of an ionization front (*32*–*34*), indicating that the radiation field reaching the disk is dominated by FUV photons.

We obtained near-infrared and submillimeter observations of d203-506, with the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA), respectively, both at angular resolution ~0.1″ (corresponding to ~40 au at the distance of the Orion Nebula). JWST images were taken in multiple broad and narrow band filters using the Near-Infrared Camera (NIRCam) instrument (*35*). We also obtained near-infrared spectroscopic observations using the integral field unit (IFU) of the Near-Infrared Spectrograph (NIRSpec) instrument on JWST (*35*). The ALMA interferometric data cubes provided maps of rotational emission lines from the molecules HCN and HCO^+, with a velocity resolution of 0.2 km s^{-1} (*35*).

Figure 2 compares the JWST and ALMA images to archival optical images from the Hubble

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[1]Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Centre National de la Recherche Scientifique (CNRS), Centre National d'Etudes Spatiales, 31028 Toulouse, France. [2]Institut d'Astrophysique Spatiale, Université Paris-Saclay, CNRS, 91405 Orsay, France. [3]Department of Physics and Astronomy, The University of Western Ontario, London, ON N6A 3K7, Canada. [4]Institute for Earth and Space Exploration, The University of Western Ontario, London, ON N6A 3K7, Canada. [5]Carl Sagan Center, Search for ExtraTerrestrial Intelligence Institute, Mountain View, CA 94043, USA. [6]Laboratoire d'Etudes du Rayonnement et de la Matière, Observatoire de Paris, Université Paris Science et Lettres, CNRS, Sorbonne Universités, F-92190 Meudon, France. [7]School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, UK. [8]UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill EH9 3HJ, UK. [9]Space Telescope Science Institute, Baltimore, MD 21218, USA. [10]Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA. [11]ACRI-ST, Centre d'Etudes et de Recherche de Grasse, F-06130 Grasse, France. [12]Innovative Common Laboratory for Space Spectroscopy, 06130 Grasse, France. [13]NASA Ames Research Center, Moffett Field, CA 94035, USA. [14]Instituto de Física Fundamental, Consejo Superior de Investigaciones Científicas, 28006 Madrid, Spain. [15]Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, CNRS, 91405 Orsay, France. [16]Centro de Astrobiología, Consejo Superior de Investigaciones Científicas, and Instituto Nacional de Técnica Aeroespacial, 28850 Torrejón de Ardoz, Spain. [17]Johns Hopkins University, Baltimore, MD 21218, USA. [18]Institut de Planétologie et d'Astrophysique de Grenoble, Université Grenoble Alpes, CNRS, F-38000 Grenoble, France. [19]Institut de Radioastronomie Millimétrique, F-38406 Saint-Martin d'Hères, France. [20]I. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany. [21]Department of Astronomy, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan. [22]Department of Physics, Faculty of Science and Engineering, Meisei University, Hino, Tokyo 191-8506, Japan. [23]Astronomy Department, University of Maryland, College Park, MD 20742, USA. [24]Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden. [25]Leiden Observatory, Leiden University, 2300 RA Leiden, Netherlands. [26]Instituto de Astrofísica e Ciências do Espaço, P-1349-018 Lisboa, Portugal.
***Corresponding author. Email: olivier.berne@irap.omp.eu**
†PDRs4All Team authors and affiliations are listed in the supplementary materials.

Space Telescope (HST). The nearly edge-on (*35*) dusty disk of d203-506 is visible in absorption in all the HST and JWST images (Fig. 2, A to F) but in emission in the 344-GHz (870 μm) dust continuum (Fig. 2G). It is also seen in emission with ALMA in Fig. 2H, which shows the HCN ($v = 0, J = 4 \rightarrow 3$) line, where v and J denote the vibrational and rotational quantum numbers, respectively, at 354.505 GHz (845.664 μm), which traces cold molecular gas. Figure 2, I and E, shows emission maps of ALMA HCO$^+$ ($v = 0, J = 4 \rightarrow 3$) at 356.734 GHz (840.381 μm) and NIRCam H_2 ($v = 1 \rightarrow 0, J = 3 \rightarrow 1$) at 2.12 μm, respectively, which both show emission from the PDR surrounding the disk and absorption at the center. Both the H_2 rovibrational and HCO$^+$ rotational emission lines trace warm (gas kinetic temperatures T_{gas} ~ 500 to 1000 K)

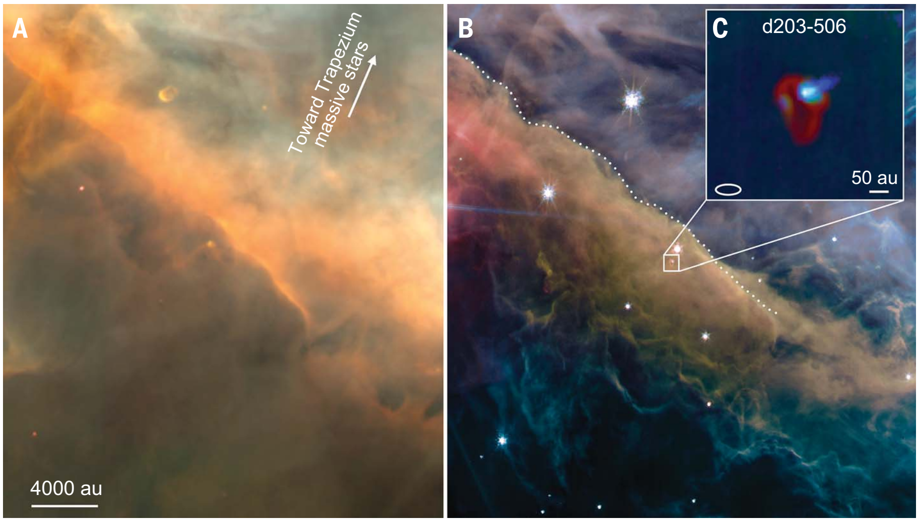

Fig. 1. Optical and near-infared images of the Orion Bar region. (**A**) HST optical image centered at coordinates right ascension 5^{h}35^{m}20^s.183 and declination −5°25′06″.14. [O III] filter at 502 nm is in blue, Hα filter at 656 nm is in green, and [N II] filter at 658 nm is in red. [Credit: NASA/STScI/Rice University/C. O'Dell *et al.* (*47*)]. (**B**) JWST near-infrared image of the same region at the same scale. Filters centered at 1.4 and 2.0 μm are in blue; at 2.77, 3.00, 3.23, 3.35, and 3.32 μm in green; at 4.05 μm in orange; and at 4.44, 4.80, and 4.70 μm in red. In (A) and (B), the Orion Bar separates regions where the gas is fully ionized (upper right) from those where it is in neutral form (lower left). (**C**) Zoomed-in view of the d203-506 disk. Red is the NIRCam image in the 2.12-μm filter, which traces molecular hydrogen; blue is the 1.64-μm filter, which traces [Fe II] emission lines; and green is the emission in the 1.40-μm broad-band filter, which traces scattered light.

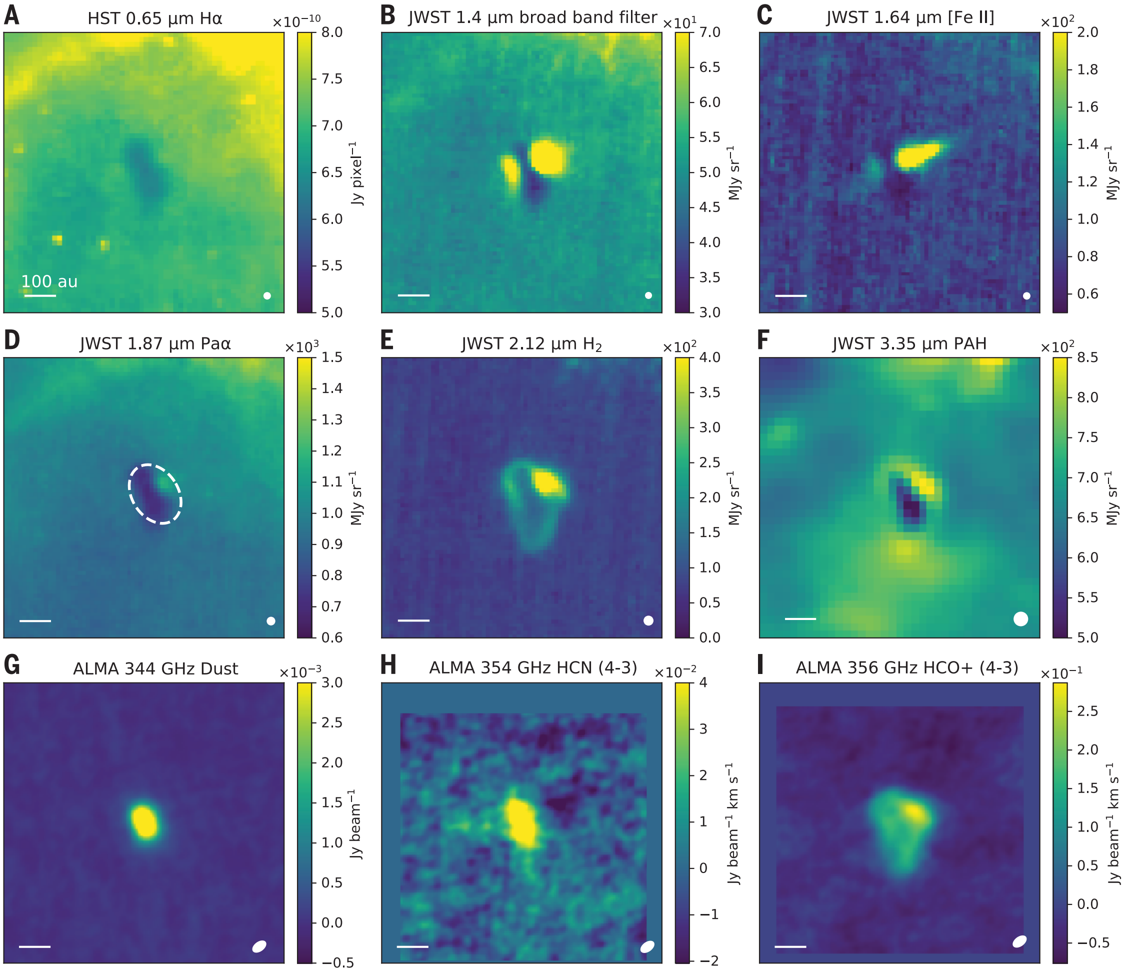

Fig. 2. Multiwavelength images of the d203-506 disk. (**A**) HST optical image in a Hα filter (*23*). (**B** to **F**) JWST near-infrared images (*35*). [(E) is reproduced with permission from (*33*)]. (**G** to **I**) ALMA submillimeter images (*35*). In all panels, the white-filled ellipse indicates the size and shape of the point spread function or reconstructed telescope beam, and the horizontal bar is 100 au. The white-dashed ellipse in (D) indicates the shape of the aperture used for the extraction of the NIRSpec spectrum in Fig. 4. The wavelength and physical assignment of each image is labeled above each panel; in (H) and (I), (4-3) is an abbreviation of (v = 0, J = 4 → 3). 1 Jy = 1 × 10^{-26} Wm^{-2} Hz^{-1}.

molecular gas in PDRs (*31*). The PDR is also bright in the 3.35-μm NIRCam filter (Fig. 2F), which is dominated by aromatic infrared band (AIB) emission from ultraviolet-excited polycyclic aromatic hydrocarbon (PAH) molecules. PAHs are known to be tracers of PDRs (*36*) and have been previously mapped in a proplyd in the Orion Nebula (*37*). The PDR in d203-506 is spatially resolved and extends south from the disk, forming a lobe shape. A jet is visible in the NIRCam [Fe II] filter at 1.62 μm (Fig. 2C). A bright emission spot is present in the H_2 and HCO^+ images in the northwestern part of the PDR and is also visible in the broad-band filter at 1.4 μm (Fig. 2B). The location of this bright spot coincides with the region of interaction between the jet and the PDR, which is visible only on the side facing the Trapezium Cluster. There is also AIB emission in the 3.35-μm NIRCam filter at this location (Fig. 2F), which indicates ultraviolet excitation. Figure 3 shows a schematic diagram of our interpretation of the morphological features in d203-506.

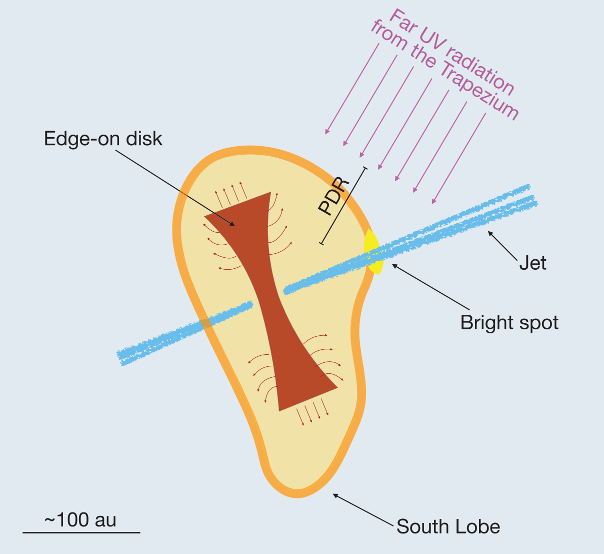

Fig. 3. Schematic diagram of our interpretation of d203-506. Dark brown is the edge-on disk of cold molecular gas, which appears in absorption in the NIRCam images but in emission in the ALMA HCN and dust continuum images (Fig. 2). Brown arrows indicate molecular gas escaping from this disk, which feeds the photoevaporation flow. This produces an envelope around the disk (light brown shading), which is delimited by the dissociation front (orange band), where molecular hydrogen is dissociated into hydrogen atoms by FUV photons (pink arrows) coming from the Trapezium Cluster. The transition from molecular gas in the disk to atomic gas under ultraviolet irradiation constitutes the PDR. Blue shows the jet from the central star, which corresponds to the [Fe II] emission (Fig. 2C). The jet interacts with the envelope, producing a bright emission spot (yellow). The surroundings of d203-506 (gray) consist of diffuse atomic gas.

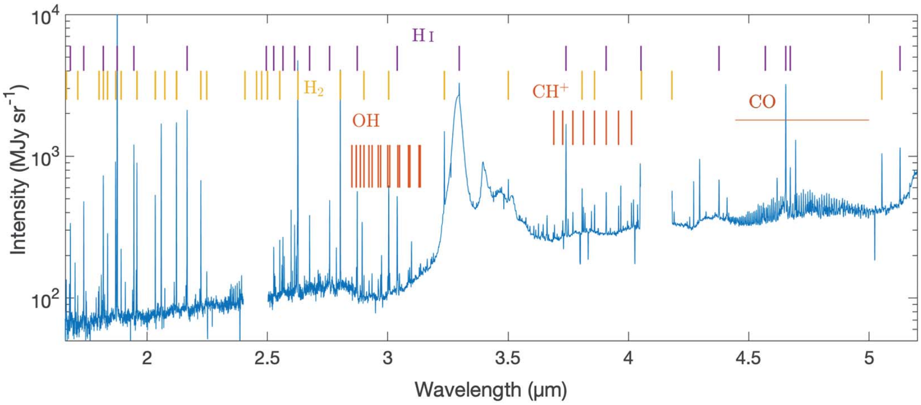

Fig. 4. JWST NIRSpec spectrum of d203-506. Colored tick marks indicate detected species, as labeled. The broad emission bands at 3.3 and 3.4 μm are C-H vibrational emission from PAH molecules. Other unlabeled lines are mostly atomic (e.g., [O I] or [Fe II]). There are no data at wavelengths 2.40 to 2.50 μm and 4.05 to 4.18 μm owing to gaps in the NIRSpec detectors.

Physical properties of the PDR

Figure 4 shows the NIRSpec spectrum of d203-506 (*35*). Numerous rovibrational emission lines of CO ($v = 1 \rightarrow 0$ and $v = 2 \rightarrow 1$), OH ($v = 1 \rightarrow 0$), CH^+ ($v = 1 \rightarrow 0$), and H_2 (up to $J = 15$) are detected. We interpreted these lines as coming from the PDR, so we traced the physical conditions of gas in that region. We modeled (*35*) the H_2 lines using the Meudon PDR code (*38*), which calculates the H_2 excitation in PDRs (Fig. 5). We derived the hydrogen number density n_H and temperature of the gas in the H_2 emitting layer (compare with Figure 2E) as $n_H = 5.5 \times 10^5$ to 1.0×10^7 cm^{-3} and T_{gas} = 1240 to 1260 K.

We fitted a Keplerian orbit model to the HCN emission map (fig. S2) and used it to set an upper limit on the mass of d203-506's central star $M_* < 0.3\, M_\odot$ (*35*). Taking $T_{gas} \sim$ 1250 K as determined above, the speed of sound $c_S \equiv \sqrt{\frac{7/5 k_B T_{gas}}{\mu m_H}} = 3.3$ km s^{-1}, where k_B is the Boltzmann constant, m_H is the mass of the hydrogen atom, and μ is the ratio of total mass to hydrogen mass of the gas, which we assume equals the interstellar value [μ = 1.4 (*39*)].

This value of c_S exceeds the escape velocity at distances from the central star above a critical value, defined as the gravitational radius $r_g \equiv \frac{GM_*}{c_S{}^2}$ (*40*), where G is Newton's gravitational constant. For $M_* < 0.3\, M_\odot$ and $T_{gas} \sim$ 1250 K, we found $r_g < 26$ au. This is much smaller than the observed radial extent of the H_2 emission $r_{H_2} = 132 \pm 13$ au [and its height $h_{H_2} = 56 \pm 13$ au (*35*)]. Therefore, the gas in this layer is not gravitationally bound and flows outward from the disk, at roughly the speed of sound. The associated mass flux through the PDR is $j = \mu m_H n_H c_S$, and the total mass loss rate is $\dot{M} = j \times S$, where S is the surface area of the H_2-emitting layer (*35*). Including the uncertainties on r_{H_2}, h_{H_2}, n_H, and T_{gas} (table S1), we calculated $\dot{M} = 1.4 \times 10^{-7}$ to 4.6×10^{-6} $M_\odot$ year^{-1}.

We also investigated an alternative method of determining the mass-loss rate, using 1D dynamical models, and found a consistent value of $\dot{M}$ (*35*). All the physical quantities that we derived are listed in table S1.

Implications for planet formation

Gas in protoplanetary disks is the raw material from which giant planets form, so mass loss due to photoevaporation can limit the formation of such planets. The effects of FUV radiation depend on the stellar mass, which sets the strength of the gravitational field that acts to retain the gas.

Theoretical models of planet growth under the influence of external FUV photoevaporation have predicted that FUV radiation fields with intensity $G_0 \gtrsim 500$ [where G_0 is the ratio of the ultraviolet radiation field to the average value in the interstellar medium (*41*)] suppress giant planet formation around stars with masses $\lesssim 0.5\, M_\odot$ (*22*). Our results for d203-506 are consistent with this prediction: We found that $M_* < 0.3\, M_\odot$ and the radiation field is $G_0 \lesssim 10^5$ (*35*), whereas the mass-loss rate $\dot{M} = 1.4 \times 10^{-7}$ to 4.6×10^{-6} $M_\odot$ year^{-1} implies a disk depletion timescale $\tau \equiv M_d/\dot{M} <$ 0.13 million years, where M_d is the disk mass

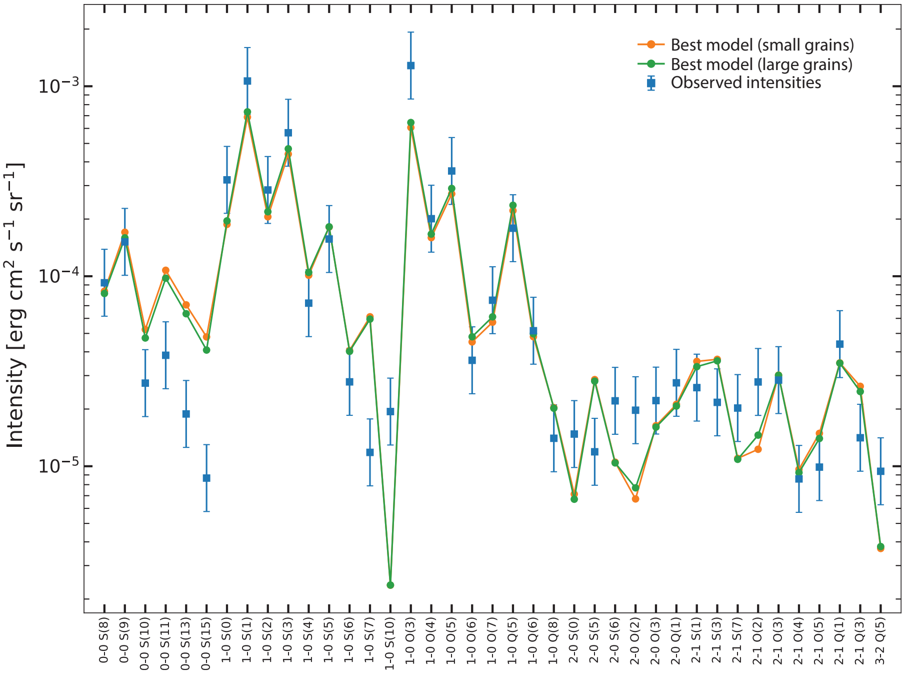

Fig. 5. Observed and modeled H_2. Line intensities for d203-506. Blue squares show the observed line intensities (table S2), with error bars enclosing 50% uncertainty, estimated from the χ^2 (*35*). The instrumental uncertainties are smaller than the symbols. Colored lines are the best-fitting models (*35*) using small dust grains (orange) or large dust grains (green); circles show the model intensities of each line. H_2 line identifications are abbreviated; the full quantum levels corresponding to this notation are listed in table S2.

(*35*). This is faster than even very early planet formation (*42*, *43*).

A positive correlation has been observed between stellar mass and the frequency of Jupiter-mass exoplanets orbiting those stars (*44*, *45*), which we suggest could be due to FUV radiation in stellar clusters during the planet formation process. Dynamical and compositional studies of the Solar System indicate that it formed in a stellar cluster that contained one or more massive stars (*46*), and so it might have been affected by FUV radiation.

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NIRCam data. I.S. extracted the NIRSpec spectrum. I.S. and M.Z. measured the line intensities. M.Z. produced the LTE radiative transfer models of CH^+ and OH. J.C. provided the radiative transfer models for CO. All other authors contributed to the research presented in this paper or provided detailed feedback on the manuscript. All authors meet the journal's authorship requirements. **Competing interests:** The authors declare no competing interests. **Data and material availability:** The JWST and HST data are available on the MAST portal http://mast.stsci.edu under the proposal IDs 1288 and 6603, respectively. The ALMA raw data are available on the ALMA archive at https://almascience.eso.org/aq under project code 2017.1.01478.S. Our reduced ALMA data cubes and maps are archived at Zenodo (*48*), as is our reduced NIRSPec spectrum of d203-506 (*49*). The modified Meudon PDR code used in this paper is available at Zenodo (*50*). **License information:** Copyright © 2024 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. https://www.science.org/about/science-licenses-journal-article-reuse

SUPPLEMENTARY MATERIALS

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Materials and Methods
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